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TELEMETRY PILL MEASUREMENT OF CORE TEMPERATURE DURING ACTIVE HEATING AND COOLING

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

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The agreement between core temperature measurements obtained using an ingestible temperature pill telemetry system (T_{pill}) and rectal (T_{re}) and esophageal (T_{es}) thermocouples was compared under conditions of both increasing and decreasing body temperature. Nine subjects participated in four 3-h trials: cold (18°C) water rest (CWR); cold water exercise (CWE); warm (36°C) water rest (WWR); and warm water exercise (WWE). During exercise trials, subjects completed three bouts of 15-min rest, followed by 45-min exercise on a cycle ergometer at 50% of peak oxygen uptake. The temperature pill was taken 10-12 h before testing. Root mean squared deviation (RMSD) was calculated for each pair of measurements (T_{pill} vs. T_{re}, T_{pill} vs. T_{es}, T_{re} vs. T_{es}) for each trial. An RMSD of "0" indicates perfect agreement, and as RMSD increases, agreement worsens. On CWR, the RMSD for T_{pill}-T_{es} (0.23±0.04) was lower ($P<0.05$) than for T_{pill}-T_{re} (0.43±0.10) or T_{re}-T_{es} (0.46±0.09). There were no significant differences in RMSD between measurement pairs on any other trial (overall average RMSD=0.26°C). These results suggest the telemetry pill system provides a valid measurement of core temperature during conditions of decreasing as well as increasing body temperature and during steady state.

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EXECUTIVE SUMMARY

The purpose of this study was to compare the agreement between core temperature measurements obtained using an ingestible temperature pill telemetry system (T_{pill}) with those obtained from rectal (T_{re}) and esophageal (T_{es}) thermocouples under conditions of both increasing and decreasing body temperature. Nine subjects participated in four 3-h trials: cold (18°C) water rest (CWR); cold water exercise (CWE); warm (36°C) water rest (WWR); and warm water exercise (WWE). Subjects were immersed to the neck for each trial. During resting trials, subjects sat quietly. During exercise trials, subjects completed three bouts of 15-min rest, followed by 45-min exercise on a cycle ergometer at 50% of peak oxygen uptake. The temperature pill was taken 10-12 h before testing, after which the subjects fasted. The trials created conditions of constantly decreasing (CWR) or increasing (WWR) core temperature, as well as periods of oscillating core temperature (CWE and WWE). Root mean squared deviation (RMSD) was calculated for each pair of measurements (T_{pill} vs. T_{re}, T_{pill} vs. T_{es}, T_{re} vs. T_{es}) for each trial. An RMSD of "0" indicates perfect agreement, and as RMSD increases, agreement worsens. On CWR, the RMSD for T_{pill}-T_{es} (0.23±0.04) was lower ($P<0.05$) than for T_{pill}-T_{re} (0.43±0.10) or T_{re}-T_{es} (0.46±0.09). There were no significant differences in RMSD between measurement pairs on any other trial (overall average RMSD=0.26°C). Telemetry pill temperature and response time tended to be intermediate between T_{re} and T_{es}. These results suggest the telemetry pill system provides a valid measurement of core temperature during conditions of decreasing as well as increasing body temperature and during steady state.

INTRODUCTION

Monitoring body core temperature unobtrusively in active subjects is difficult. Esophageal and rectal temperature, generally considered the most reliable and precise indices of core temperature (Sawka and Wenger, 1988), are invasive measurements and require a wire connection between the sensor and monitoring/recording device. Thus, these measurement methods are unsuitable for physiological monitoring of ambulatory, unrestrained subjects. For these applications, ingestible temperature sensors offer an acceptable alternative.

Ingestible temperature pill telemetry systems provide a valid measure of core temperature during rest and exercise in warm or neutral ambient conditions (Sparling et al., 1993; Kolka et al., 1993). However, the validity of the temperature pill measurements during cold exposure has not been demonstrated. Therefore, the aim of this study was to compare measurements obtained from an ingestible telemetric temperature pill with those from esophageal and rectal thermocouples during cold as well as hot conditions. The validity of the temperature pill measurement for monitoring core temperature was thus determined during conditions of decreasing as well as increasing body temperature.

METHODS

SUBJECTS

Nine healthy soldiers (four male, five female) participated in this study. The subjects had the following characteristics: age=25±2 yr; weight=73±3 kg; height=166±3 cm; peak oxygen uptake=3.1±0.4 l/min. All subjects voluntarily consented to participate after being informed of the purpose, procedures, and known risks of these experiments, which were approved by the appropriate institutional review boards. Female volunteers were screened for pregnancy, which was an exclusionary criterion. All soldiers were in compliance with the Army height and weight standards (males less than 22% fat; females less than 32% fat) (Department of the Army, 1986).

Peak oxygen uptake was determined using a continuous effort, progressive intensity stationary cycle ergometer protocol. After a brief warmup, subjects pedaled for 2 min at 60 rpm against zero resistance; thereafter, the power output was increased 30 W every 2 min until the subject was unable to continue in spite of verbal encouragement. Oxygen uptake, carbon dioxide output, and minute ventilation were measured continuously throughout. Peak oxygen uptake was defined as the highest oxygen uptake achieved. Heart rate, monitored using an electrocardiogram obtained from chest electrodes (CM-5 placement) and radio telemetered to an oscilloscope-cardiotachometer, was recorded at the end of each stage.

PROTOCOL

The study employed a repeated measures design in which each subject served as his/her own control. Each volunteer participated in four 3-h immersion trials: a) cold (18°C) water rest (CWR), to produce a continuous decrease in core temperature (T_c); b) cold water exercise (CWE), to produce an oscillation in T_c superimposed over a generally decreasing T_c; c) warm (36°C) water rest (WWR), to produce a continuous increase in T_c; and d) warm water exercise (WWE), to produce an oscillation in T_c superimposed over a generally increasing T_c. Exercise consisted of three repeated bouts of 15-min rest followed by 45-min cycling at 50% of the individual's peak oxygen uptake.

TELEMETRY PILL SYSTEM

The ingestible telemetric temperature system consisted of a commercial temperature pill, 2 cm in length x 1.2 cm diameter (CorTemp™, Human Technologies, Inc., St. Petersburg, FL), and a compact data receiver/logger (BBN Systems and Technologies, Cambridge, MA). The temperature pill consists of a temperature-sensitive quartz crystal oscillator with a silver oxide battery, encapsulated in epoxy and covered with silicone rubber. This sensor transmits a continuous, low-frequency radio wave which varies with temperature. This signal is received and stored by the data logger and later downloaded to a computer after completion of data collection.

A linear relationship exists between signal frequency and temperature. While the slope constant of this relationship is similar from pill to pill, the intercept varies. Although the pills are individually calibrated by the manufacturer, the accuracy and precision of the calibration of each pill was confirmed in our laboratory using the same data loggers as used in the experiments. An individual linear regression relationship of temperature-to-frequency was derived for each pill based on the frequency emitted after equilibration in a water bath at three temperatures (33°C, 37°C, 41°C). This regression equation was used to convert frequencies transmitted by the pill into temperature values. Each pill had a correlation coefficient between water bath temperature and frequency emitted greater than 0.999.

EXPERIMENTAL PROCEDURES

Subjects began fasting at 1900 h on the evening before each immersion test. The telemetric temperature pill was then ingested at 2000 h. Subjects were allowed to ingest as much water as necessary to swallow the pill, but thereafter refrained from food or fluid intake until arriving at the laboratory at 0700 h the next morning. After voiding and having their nude weight measured, they consumed 235 ml of a commercial meal-replacement beverage (Ensure, Ross Products Division, Abbott Laboratories, Columbus, OH). The rectal thermocouple was inserted 10 cm into the rectum; the esophageal thermocouple was inserted through the nose to the level of the heart, estimated as 1/4 of the subject's height. All thermocouples (copper-constantan,

Physitemp Instruments, Inc., Clifton, NJ) were tested prior to use to verify that they were accurate within ±0.1°C. The trials all began at approximately 0800 h.

For the experiments, subjects sat with their legs extended on the pedals of a semirecumbent cycle ergometer modified for use in water. Fly-wheel resistance was adjusted by attaching fins of varying length to the flywheel, similar to the method employed by Shapiro et al. (Shapiro et al., 1981). The seat and back of the chair were constructed of stainless steel, perforated to facilitate water movement around the subject and minimize the formation of a still boundary layer. Subjects wore aquatic sport sandles, open at the top, toes, and sides, to protect the bottom of the feet during pedaling. The ergometer was mounted on a platform that could be raised and lowered in and out of a 30,000 l pool in which water was continuously circulated and temperature maintained within ±0.1°C of the desired temperature. The water level was adjusted to cover the subjects' shoulders while they were immersed. During the exercise trials, subjects rested for the first 15 min of each hour, then pedaled at a rate of 40 rpm for 45 min. This cycle was repeated three times, for a total of 3-h immersion. The resistance was adjusted to a predetermined setting designed to elicit an oxygen uptake equivalent to 50% of peak oxygen uptake. Heart rate was monitored continuously during immersion. Rectal and esophageal temperatures were measured and recorded every 30 sec throughout immersion using an automated data acquisition system. Pill temperature data were recorded every 15 sec throughout immersion by data loggers attached to a belt around the waist of the subject. Metabolic rate was measured from the 5th to the 10th minute and from the 50th to 55th minute of each hour of immersion. At the end of each hour of immersion subjects were allowed to drink 200 ml of water.

STATISTICAL ANALYSIS

To compare temperature pill measurements (T_{pill}) with the corresponding rectal (T_{re}) and esophageal (T_{es}) temperature measurements, the root mean square deviation (RMSD) between the corresponding time series temperature data every 30 seconds (T_{pill} vs. T_{re}; T_{pill} vs. T_{es}; T_{re} vs. T_{es}) was calculated for each subject on each trial as described by Haslam and Parsons (Haslam and Parsons, 1988). The RMSD provides an estimate of the agreement between two measures of a single parameter, in this

case, core temperature. Agreement is perfect when RMSD=0. To determine whether exercise and water temperature influenced the agreement between T_{pill} and T_{re} and T_{es}, the RMSD values were compared using a two-way (measurement x trial) repeated measures analysis of variance (ANOVA). ANOVA was also conducted to compare measurements over time during each trial. For this analysis, representative data at 10 min time points were used; i.e., 19 data points per trial. In addition, pre-immersion temperatures were compared by ANOVA. Post-hoc analysis of significant ($P<0.05$) main effects (i.e., significant differences between measurements) was by Tukey's HSD test. Data are presented as mean±SEM.

RESULTS

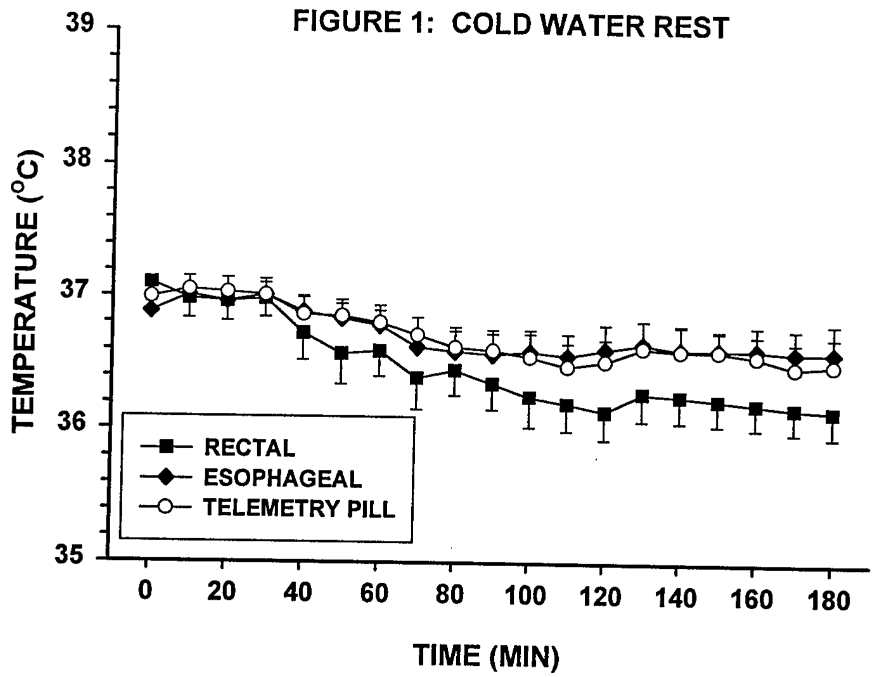
On three occasions, T_{pill} signal was not detected from a subject on the morning of the trial. In these instances, a new pill was ingested, and the trial postponed 1 hour. The T_{pill} data for these subjects were within two standard deviations of the mean T_{pill} from all other subjects, and were therefore included in the statistical analyses. At the end of each hour, coincident with when subjects were allowed to drink water, a transient decrease in T_{es} was always observed. For the data analysis, these data (the drinking-associated depression) were deleted, since they reflected the transient local cooling effect of water ingestion on the esophagus.

The RMSD ($\bar{X}$±SEM) for each measurement pair (T_{pill}-T_{re}, T_{pill}-T_{es}, T_{re}-T_{es}) on each trial is presented in Table 1. On CWR, the RMSD for T_{pill}-T_{es} was lower ($P<0.05$) than for T_{pill}-T_{re} or T_{re}-T_{es}, as indicated by *. There were no other differences between measurement pairs or trials.

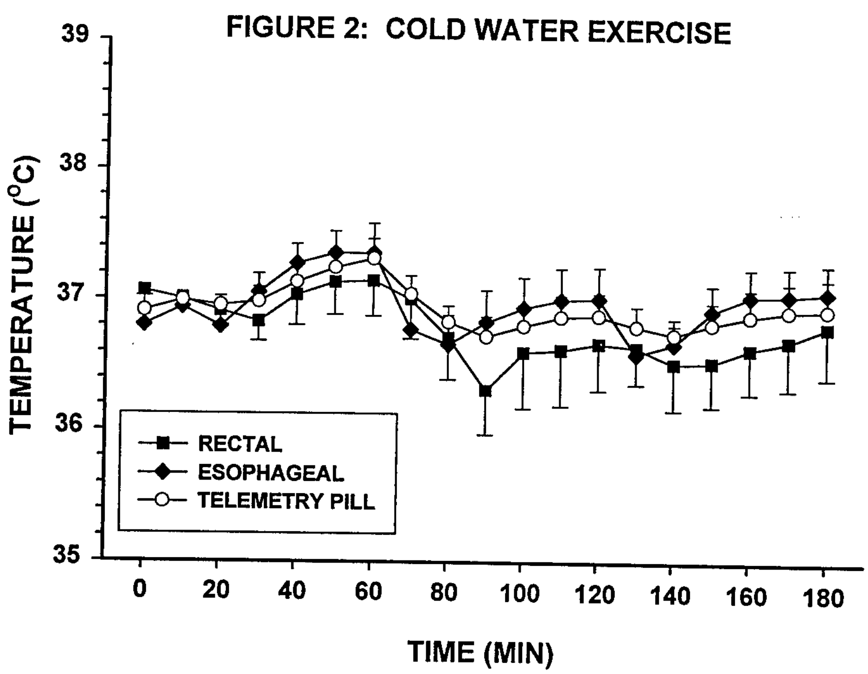
TABLE 1. Root Mean Squared Deviation (°C)

	T_{pill} - T_{re}	T_{pill} - T_{es}	T_{re} - T_{es}
Cold Water Rest	0.43±0.10	0.23±0.04*	0.46±0.09
Cold Water Exercise	0.36±0.08	0.24±0.02	0.35±0.06
Warm Water Rest	0.15±0.03	0.25±0.05	0.17±0.02
Warm Water Exercise	0.22±0.06	0.26±0.03	0.30±0.03

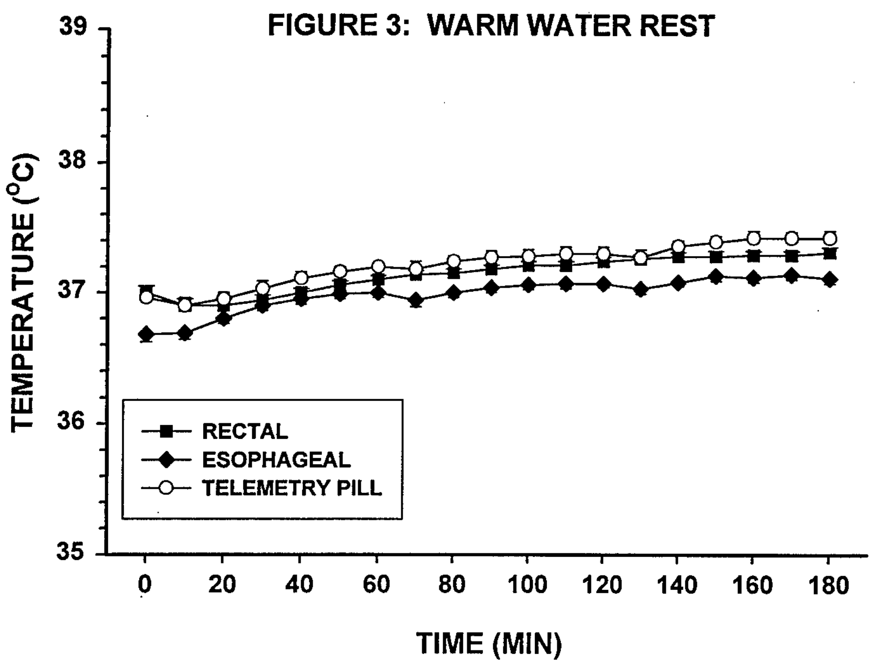
Data at 10-min timepoints for CWR is shown in Figure 1. Pre-immersion T_{pill} did not differ from either T_{re} or T_{es}; however, T_{re} was higher (0.2±0.1°C, $P<0.05$) than T_{es}. Temperature fell continuously during CWR (T_{pill}, -0.6±0.1°C; T_{re}, -1.4±0.2°C; T_{es}, -0.4±0.1°C). During CWR, T_{pill} and T_{es} did not differ from each other, but both were higher ($P<0.05$) than T_{re}.



Data at 10-min timepoints for CWE is shown in Figure 2. Pre-immersion T_{pill} did not differ from either T_{re} or T_{es}; however, T_{re} was higher (0.3±0.1°C, P<0.05) than T_{es}. The mean difference between highest and lowest temperature achieved during CWE was 1.2±0.1°C for T_{pill}, 1.2±0.1°C for T_{re}, and 1.4±0.1°C for T_{es}. There were no differences between measurements across the trial.



Data at 10-min timepoints for WWR is shown in Figure 3. Pre-immersion T_{es} was lower (0.3±0.1°C, P<0.05) than both T_{pill} and T_{re}, which did not differ. Temperature rose continuously during WWR (T_{pill}, 0.5±0.1°C; T_{re}, 0.3±0.1°C; T_{es}, 0.4±0.1°C). There was no difference between T_{pill} and T_{re}, but both were higher (P<0.05) than T_{es}.



Data at 10-min timepoints for WWE is shown in Figure 4. Pre-immersion T_{pill} did not differ from T_{re} or T_{es}; however, T_{re} was higher (0.2±0.1°C, P<0.05) than T_{es}. The mean difference for each subject between highest and lowest temperature achieved during WWE was 1.5±0.2°C for T_{pill}, 1.4±0.2°C for T_{re}, and 1.5±0.2°C for T_{es}. On WWE, there was no difference between T_{pill} and T_{re}, but both were higher (P<0.05) than T_{es}.

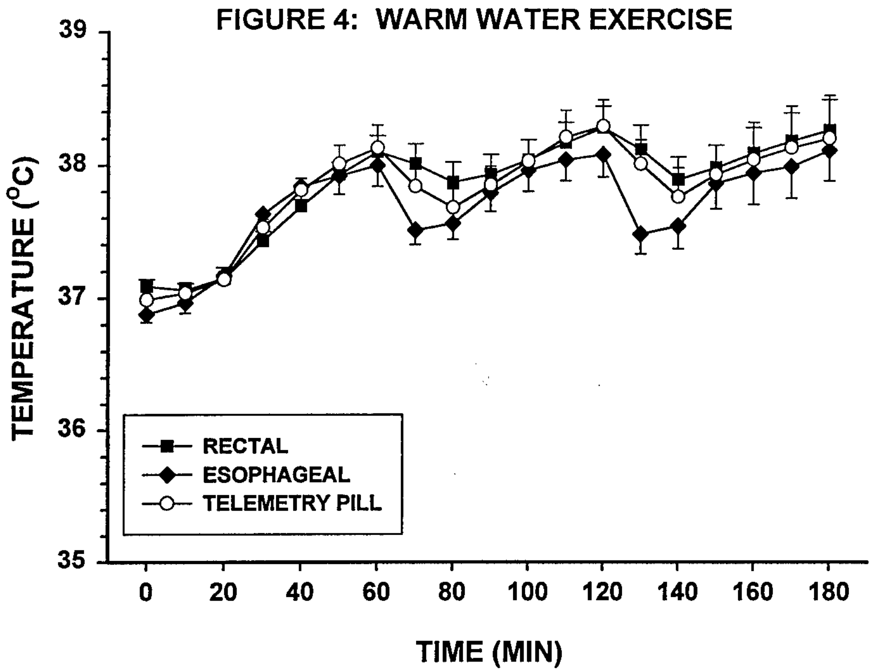


FIGURE 4: WARM WATER EXERCISE
TEMPERATURE (°C)
39
38
37
36
35
0
20
40
60
80
100
120
140
160
180
TIME (MIN)
RECTAL
ESOPHAGEAL
TELEMETRY PILL

DISCUSSION

The purpose of this study was to extend previous findings demonstrating the validity of a telemetry pill for core temperature measurement in warm conditions by validating the pill system for measurement of core temperature in cold conditions. The trials successfully created the desired conditions of both rising and falling core temperature. During resting trials, a steady change in temperature occurred. The exercise trials showed a general change in temperature throughout the trial, with oscillations in temperature created by alternating rest and exercise.

Both T_{es} and T_{re} are widely accepted as valid measurements of core temperature, hence were used as standards against which T_{pill} is evaluated. Previous studies compared T_{pill} to T_{es} or T_{re} at selected discreet time points during rest or steady state exercise. However, a comparison of the measurements throughout an entire experimental period has never been reported. The root mean squared deviation used in our analysis does this by comparing each pair of measurements at all time points during the experiment to determine the overall mean deviation of one measurement relative to the other. This analysis demonstrated that the agreement between T_{pill} and T_{re} or T_{es} was similar to the agreement between T_{re} and T_{es} under all conditions studied. Thus, T_{pill} appears to be a valid method for measurement of core temperature in humans during conditions of both decreasing, as well as increasing, body temperature.

The advantages and limitations of differing sites and methodologies of measurements of human core temperature and the physiological mechanisms accounting for differences in the core temperature measured by those methodologies are considered in detail elsewhere (Sawka and Wenger, 1988). As others have reported (Kolka et al., 1993), we observed that T_{re} was generally higher than T_{es}, and that T_{pill} was typically intermediate. The exception to this was during the resting cold water trial. When seated at rest in cold water, subjects in this study displayed a lower T_{re}, compared to T_{pill} or T_{es}. This may reflect facilitated conductive heat loss from the subject's lower torso and limbs, as the subjects sat on a chair made of stainless steel, which has a higher heat transfer coefficient than water alone. During the warm water trials T_{es} was lower than T_{re} or T_{pill}, which may be due to a lower heat capacity of the esophagus, thus a closer reflection of blood temperature. These explanations are

speculative, but might suggest some considerations for selecting a measurement method.

The telemetry pill has been criticized as subject to variations in temperature that occur due to its movement through the gastrointestinal tract (Kolka et al., 1993; Livingstone et al., 1983). This effect was not evident during the 3-h trials in which temperature was monitored in this study. Since the subjects took the telemetry pill 12 h before the trial, versus 2-3 h in previous studies (Kolka et al., 1993), fluctuation in temperature as the pill passed through the stomach and past the liver (commonly cited as areas of temperature variability) may have been avoided. Temperature in the small and large intestines is probably more uniform than in the upper portion of the gastrointestinal tract. Further study of pill temperature variations over the entire time course of pill transit through the gastrointestinal tract is required to confirm this speculation. However, the magnitude of fluctuation attributed to pill movement, 0.2-0.3°C (Kolka et al., 1993), is not likely to be of physiological significance for many applications. In addition, while T_{es} and T_{re} have the benefit of a fixed anatomical position, these measurements are often not practical for assessing core temperature in studies involving large numbers of free-living, ambulatory test subjects. For those and other applications, a telemetry pill system is a valid alternative for assessing core temperature.

In summary, this study demonstrates that the ingestible temperature telemetry pill system provides a valid measurement of core temperature during both rest and exercise in cold as well as warm conditions. Further study, however, to better quantify the variation in core temperature measured by the pill as it transits the gastrointestinal tract is warranted. The pill system is particularly appropriate for monitoring core temperature in field environments where other techniques are not feasible.

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